NPS-61SW71011A

United States Naval Postgraduate School

REPORT ON THE IV EUROPEAN CONFERENCE ON

CONTROLLED FUSION AND PLASMA PHYSICS

Rome, Italy, 31 August - 4 September 1970

by

F. Schwirzke

26 January 1971

NAVAL POSTGRADUATE SCHOOL
Monterey, California

Rear Admiral R. W. McNitt, USN
Superintendent

M. U. Clauser
Academic Dean

ABSTRACT:

The titles of the 17 sessions and the 6 invited lectures are summarized in the introduction. Concerning the content of the 191 presented papers, only the ones referring to toroidal confinement, laser produced plasmas, collisionless shocks and turbulent heating are reviewed in this report, as for example: papers presented by the Russian participants on particle confinement, energy balance, ion and electron thermal conduction, anomalous resistivity, current diffusion and skin depth in tokamaks.

The second part of the report contains the paper No. 114, "Investigation of Laser Produced Plasmas in a Magnetic Field" by F. Schwirzke. All mentioned papers have been published in the conference book entitled, Fourth European Conference on Controlled Fusion and Plasma Physics, Rome Italy, C. N. E. N. Ufficio Edizioni Scientifiche, (1970).

CONTENTS

PART A

PART B

PART A

Report on the IV European Conference on

Controlled Fusion and Plasma Physics

Rome, Italy, 31 August - 4 September 1970

by F. Schwirzke

I. Introduction

The conference was a fourth in a series of which the previous three took place in Munich (1965), in Stockholm (1967) and in Utrecht (1969). This conference in Rome was the first to be organized by the recently founded Plasma Physics Division of the European Physical Society (EPS). There were about 400 participants from 22 countries: Italy 84, West Germany 59, France 47, USA 42, UK 40, USSR 32, Netherlands 22, Switzerland 12, Belgium 11, Czechslovakia 6, Sweden 6, Austria 4, Denmark 4, Japan 4, East Germany 3, Canada 2, Israel 2, Yugoslavia 2, Australia 1, Poland 1, Turkey 1, UAR 1.

191 papers were selected for presentation by the Paper Selecting and Program Committee. The countries contributed the following numbers of papers: USA 33, West Germany 31, France 29, USSR 27, UK 22, Italy 12, Netherlands 11, Belgium 6, Sweden 4, Switzerland 4, Czechoslovakia 2, Denmark 2, Japan 2, UAR 2, and one paper each from Austria, East Germany, Poland, Romania, and Yugoslavia.

The papers were presented in two parallel sessions. The titles of the sessions were:

(1) Toroidal Confinement (Theory)
(2) Tokamaks
(3) Stellarators
(4) Pinches
(5) Collisonless Shocks and Turbulent Heating
(6) Beam - Plasma Interactions
(7) Shock Tubes
(8) Mirrors
(9) HF-Plasmas and Heating
(10) Dense Plasmas

(11) Diagnostics
(12) Linear Waves and Instabilities I
(13) Nonlinear Phenomena I
(14) Linear Waves and Instabilities II
(15) Dynamical and Feedback Methods
(16) Nonlinear Phenomena II
(17) General Theory

The invited lectures were entitled:

(1) Conclusions of the Trieste Workshop on Theoretical Plasma Physics, by B. B. Kadomtsev, USSR.
(2) Nuclear Fusion Reactor Design - A Review by Kristiansen and Hagler, USA
(3) Survey of Screw Pinch Studies by Van der Laan, The Netherlands
(4) Review on Laser Produced Plasmas by A. Caruso, Italy
(5) Dynamic Stabilization of Perfectly Diamagnetic Plasmas by Weibel, Switzerland.
(6) Supra-Thermal Electric Field Fluctuations from Spectral Line Profile Measurements by Griem, USA.

II. Toroidal Confinement, Tokamaks.

During the years 1968, 1969, very encouraging results had been reported in confining a hot plasma of about 500 eV and a density of 4×10^{13} cm^{-3} in Tokamak machines. Only a year ago, spurred by experimental results, there was the optimistic feeling that the processes of heating and confinement in Tokamaks were nearly classical and almost understood. It is obvious from the presented papers that in the mean time the problems of equilibrium and diffusion in toroidal machines were investigated in more detail and sure enough, serious discrepancies surfaced. Rabinovich from the Lebedev Physical Institute in Moscow stated frankly in a panel discussion, "I tell you we don't understand toriodal experiments."

What are the problems? In the toroidal plasma configuration of the Tokamak machine a current has to produce the rotational transform necessary for stable confinement. This current fulfills not only the function of confining the plasma but the electrons are ohmically heated by the current to a temperature of about 1 keV. The ions are heated by Coulomb collisions with the electrons to a temperature of about 500 eV. Due to density and temperature gradients diffusion across the magnetic surfaces occurs. The mass flow limits the particle confinement times. The achievable ion temperature depends on the heating rate of the electrons and energy losses due to ion thermal conduction, diffusion and charge exchange. The classical mass diffusion across the B field in a fully ionized plasma is determined by the small electron diffusion coefficient, $D_{\perp}^{-} = (r_{ce}^2\, \nu_{ei})/3$. However, the heat is conducted across the B field by the ions mainly, due to their large gyroradius. The classical electron thermal conductivity is smaller by the ratio $(mT_i/M_iT_e)^{1/2}$ and should be negligible. Taking into account the classical transport coefficients the radial density and temperature distributions can be calculated and compared with experimental data. The energy balance and the lifetime of ions in Tokamak T-3 was examined in a paper by Artsimovich et al. (1) from the Kurchatov Institute, Moscow. The ion temperature was obtained from the analysis of the energy spectrum of a charge exchanged atoms. Depending what temperature profile one assumes, T_i explains satisfactorally the observed neutron yield which is a rather sensitive function of the ion temperature. The equation for the ion energy balance can be written,

$$0.4\ 10^{-17}\ \frac{n^2}{AT_i^{1/2}} = \frac{3}{2}\, nk\, \frac{dT_i}{dt} + \frac{3}{2}\, nk\, \frac{T_i}{\tau_E}$$

where A is the atomic weight and τ_E the time for energy loss from the ions. The term on the left hand side of the equation represents the energy passed from the electrons to the ions by Coulomb collisions per sec and cm^3. The electron temperature T_e is not included in this term, because the flux of energy from electrons to ions depends quite weakly on T_e in the range of T_e/T_i from 1.6 to 10. The experimental value of the ratio T_e/T_i is always in this range. The energy losses from the ions are caused by thermal conductivity, τ_H, diffusion, τ_D, and charge exchange, τ_C,

$$\frac{1}{\tau_E} = \frac{1}{\tau_H} + \frac{1}{\tau_D} + \frac{1}{\tau_c}$$

The values of τ_D and τ_c depend on the density n_a of atomic hydrogen or deuterium in the central region of the plasma column like $\tau_c = 1/n_a \langle \sigma v \rangle_c$

The value of n_a has been determined from absolute intensities of lines of the Balmer spectrum and from the flux of charge exchanged particles emitted from the central region of the plasma column, $n_a \approx 1.5 - 3 \times 10^8$ atoms/cm^3. Using the above values of n_a, the diffusion and charge exchange times are of the order $\tau_C \approx \tau_D \approx 0.1$ sec. A comparison with the measured $\tau_E \approx 1.5 - 20$ msec shows that $\tau_C \sim \tau_D > \tau_E$. In conclusion, the dominant energy loss mechanism is due to ion heat conduction $\tau_E \approx \tau_H$.

A scaling law for T_i can be derived, if one assumes a certain temperature profile, from theoretical consideration of Galeev and Sagdeev (2) on the classical ion heat conductivity in toroidal systems.

$$T_i = (5.9 \pm 0.5)10^{-7} \, (I \, B_z \, R^2 \bar{n})^{1/3} \, A^{-1/2}$$

where I is the discharge current in Amps, R = 100 cm is the main radius of the toroidal system, B_z in Gauss is the longitudinal magnetic field and $\bar{n}$ in cm^{-3} the average density. The experimental results in the parameter ranges I = 60 - 110 kAmps, B_z = 25 - 38 kG, $\bar{n} = 1.5 - 3.8 \times 10^{13}$ cm^{-3} are in agreement with this formula derived from the "neoclassical" theory.

The processes contributing to ion heating and ion energy losses are much better understood than the electron heating and electron thermal transport. The problems of current diffusion and electron energy balance were considered in a paper by Dnestrovskii et al, (3), from the Moscow State University. The electron energy scales as the square of the current. Beta with respect to the field of the current is about

$$\beta_\theta = \frac{2NkT}{I^2} \approx 0.45$$

near the middle of the current pulse when the transverse energy is a maximum in the plasma column. Measurements of the plasma resistance have shown that its value exceeds the classical resistance several times by a factor γ. There is still some dispute how much of the observed increase in the resistivity is due to impurities and how much is anomalous.

Now, computer simulations show a large skin effect for the current and electron temperature if classical transport coefficients are used. The current should flow on the surface where the electron temperature and correspondingly the conductivity are high and during the entire heating time of about 60 msec the current should never penetrate the whole plasma column. On the other hand, the joint British-Russian team, Gorbunov, Ivanov, Peacock, Robinson and Strelkov (4) reported in Rome Thomson scattering experiments of radial electron density and temperature distributions. The measurements show a skin effect of the temperature only early in the discharge for 4 msec. A temperature increase on the outside of the plasma of up to 1.5 times the central value was observed due to the skin currents. Nobody has actually measured the current distribution and the current diffusion into the plasma yet. To solve the problem of the skin effect one may assume an anomaly in the electron thermal transport across the magnetic field. However a too large heat transport by the electrons can work in two ways. Initially, it may help to establish a homogeneous current distribution over the discharge cross section. Later, an anomalous electron heat condition may increase the energy loss rate from the plasma column and one shouldn't obtain a hot plasma in the steady state. Also as a consequence, β_θ would be too low. Kadomtsev mentioned in his invited paper that from the analysis of the energy balance in the Tokamak follows an electron thermal conductivity which is considerably higher than the classical one. Heat from the Tokamak is lost via the electrons. This energy is not being lost by radiation but by electron thermal transport.

To overcome the problem, Dnestrovskii et al (3) studied the current diffusion by means of a phenomenological model of an anomalous resistance and electron thermal conductivity. The equations for the electron and ion energy balances which serve to calculate $T_i(x,t)$ and $T_e(x,t)$ are,

$$\frac{\partial T_i}{\partial T} = \frac{1}{nx}\frac{\partial}{\partial x}\left(xn\chi_i \frac{\partial T_i}{\partial x}\right) - \frac{A_3 N}{T_e^{3/2}}(T_i - T_e)$$

$$\frac{\partial T_e}{\partial t} = \frac{1}{nx}\frac{\partial}{\partial x}\left(xn\chi_e\gamma_1 \frac{\partial T_e}{\partial x}\right) + \frac{A_3 n}{T_e^{2/3}}(T_i - T_e) +$$

$$\frac{A_2\gamma}{nT_e^{3/2}}\left[\frac{1}{x}\frac{\partial}{\partial x}(x^2\eta)\right]^2$$

The equation for the B_θ-field which is created by the plasma currents is given by

$$\frac{\partial\eta}{\partial t} = \frac{A_1}{x}\frac{\partial}{\partial x}\left[\frac{\gamma}{T_e^{3/2}}\frac{1}{x}\frac{\partial}{\partial x}(x^2\eta)\right]$$

where $\eta = 1/q = RB_\theta/rB_z$ and $x = r/a$. R is the major radius of the torus, a = the minor radius and r the distance from the magnetic axis. The plasma density is assumed to have a profile as

$$n(x) = N(1 - 0.5x^2) \quad .$$

If the longitudinal field B_z is expressed in kGauss and the lengths are in cm, the coefficients assume the values $A_1 = 6100/a^2$, $A_2 = 2 \times 10^7\ B^2/R^2$, $A_3 = 470/M_i$ where Mi is the relative ion mass. χ_i and χ_e are the classical thermoconductivity coefficients. The fudge factors $\gamma(x,t)$ and $\gamma_1(x,t)$ allow a description of the anomalies in the resistance and electron heat conduction as function of the radius and time. In the simplest case $\gamma = \gamma_1$ = constant. In the "middle" model the numerical value of the constant is determined from the mean experimental value of the plasma resistance. This model leads usually to a slow current diffusion. Therefore the "local" model was also used which relates the anomalies in the transport coefficients to the onset of an ion sound instability. In this model $\gamma(\theta)$ is a function of the local ratio $\theta = u/c_s$ where u is the current related drift velocity of the electrons and c_s the ion sound velocity. For $\theta < 1$ the plasma behaves classically and $\gamma = 1$. If $\theta > 1$ then $\gamma(\theta)$ increases rapidly. Usually for the range $1 < \theta \leq 1 + \Delta\theta$ the following relationship was assumed

$$\gamma = \bar{\gamma}_1 = \gamma(\theta) = 1 + 0.5(\gamma_{max} - 1)(1 - \cos[\pi(\theta - 1)/\Delta\theta]) \quad .$$

While for $\theta > 1 + \Delta\theta$, γ was limited to $\gamma = \gamma_{max}$. For the computer calculations, it was set $\Delta\theta \sim 2$. $\gamma_{max} = 10$ was chosen to fit the experimentally observed values of the anomalous plasma resistance. The calculations show the occurrence of the maximum anomaly, $\gamma_{max} = 10$, early in time at 5 msec near the plasma boundary. This large value of γ leads to a sufficiently fast current diffusion. After this, γ decreases to the experimentally observed value $\gamma \approx 4$ and the current distribution doesn't show the skin effect anymore. The calculated electron temperature profile also shows a hot skin for 5 - 10 msec only. At 20 msec the T_e profile coincides with the one determined from laser scattering experiments. The maximal T_i and τ_E were calculated too as function of time and compared with experimental values. The computational results are in good agreement with the experiments on the two Tokamak devices T-3 and TM - 3.

Concerning the toroidal plasma confinement, many related problems have to be considered, namely equilibrium, diffusion and instabilities. In analyzing the diffusion flow across the field the effect of the plasma compression by the longitudinal electric field in toroidal discharges has to be taken into account. In the case of very low collision frequencies, the so called banana and plateau regimes, the plasma compression is very effective and dominates the diffusion for $\beta_\theta < 1$. This theoretical consideration is in qualitative agreement with the experimentally observed long confinement times of particles in Tokamak T-3. However, there still exist other problems to be concerned with:

1. The observed density limitations in the Tokamaks;
2. The role of runaway electrons;
3. The range over which the scaling laws are valid;
4. How the heat the plasma beyond the ohmic heating limit.

Obviously it is impossible to separate heating and confinement in Tokamaks.

In conclusion, if we believe in the scaling laws then the Tokamaks are not too far away from the ignition point for the fusion process. If the currents in the T-4 are doubled ignition temperature should be achieved. Even if the diffusion processes do not improve further, ignition temperature should be achieved with a machine twice as large in diameter, which isn't too big after all. The needed gain in confinement time is simply due to the increase in the radius. However, there is still the difficulty of heating the plasma to higher temperatures, other heating mechanisms like ion cyclotron, neutral beam injection, increased turbulent heating and adiabatic compression will probably be tried in the near future. The advantage of a strong shear, high β stellarator as a fusion reactor would be that no current in the plasma would be needed for confinement as in the case of a Tokamak.

Certainly, the Tokamak fever is spreading. New machines are being constructed at the Laboratori Gas Ionizzati in Frascati, Italy, and at the IPP in Garching, Germany.

III. Directional Ion Fluxes in a Stellarator

The existance of large toroidal fluxes in stellarator hadn't been recognized up to now. In an important contribution by Berezhetsky et al (5) from the Lebedev Institute of Physics, Moscow, the authors reported on experimental measurements of directional ion fluxes in stellarators L-I and Tor-2. The existence of closed axial ion and electron fluxes were predicted in theoretical studies on the equilibrium of a plasma column in the toroidal magnetic field of a stellarator. However, the experimentally observed flux cannot be explained qualitatively and quantitatively by the equilibrium fluxes calculated in references (6, 7). The direction and the value of the directional velocity of the ions depends on the rotational transform. The maximum drift velocity occurs near the periphery of the vacuum chamber. The drift velocity varies between 0.1 - 0.5 of the thermal ion speed. The role of the toroidal ion fluxes with respect to particle losses is not clear yet. This problem requires additional theoretical and experimental studies.

IV. Collisonless Shocks and Turbulent Heating

Investigations of instabilities in collisionless shock fronts are of great importance for the understanding of the efficiency of energy dissipation in turbulent heating experiments. Several advanced diagnostic methods have been applied to determine the plasma parameters, density and temperatuare, the drift velocities of electrons and ions, and the mean square amplitudes of ion sound waves during the turbulent heating process. The scattering of laser light has been used by several investigators to reveal the characteristics of the turbulence in the shock front.

Chodura et al (8) from Garching, Germany reported that the collective scattering of laser light shows ion wave fluctuations within the shock which are clearly enhanced by an order of magnitude above the thermal level.

The shock waves were produced by a fast rising magnetic field of a theta pinch discharge, 0.5 μs rise to 12 kG in a coil of 15.8 cm diameter and 60 cm length. The shock waves propagate into a high $\beta = 0.3 - .5$ hydrogen or deuterium plasma of density $2 - 5 \times 10^{14} cm^{-3}$ formed by a theta pinch preionization. In contrast with similar experiments at other laboratories, the ion temperature in the initial plasma is larger, $T_{i1} = 20 - 50$ eV, than the electron temperature, $T_{e1} = 3 - 8$ eV and remains higher during the shock heating process. By properly choosing the initial conditions and the voltage of the shock bank almost stationary collision-free shock waves have been produced with magnetic Mach numbers M ranging from 1.5 to 5.

Scattered ruby light was also used by Paul et al (9) from Culham, England, to measure the level of turbulence and the frequency and wave number spectrum within a collisionless shock. In this case the shock was produced by the radial compression of a magnetized plasma by a linear z-pinch, $n_{e1} = 6.4 \times 10^{14} cm^{-3}$, $T_{e1} = T_{i1} = 1.2$ eV, $B_{z1} = 1{,}200$ Gauss. The shock is in a steady state with velocity $V_s = 2.4 \times 10^7 cm\ s^{-1}$ (Alfven Mach number $M_A = 2.5$), width 1.4 mm and compression ratio 2.5. The electrons are shock heated to 44 eV, which requires about 100 times the classical resistivity. The level of turbulence for the ion waves, $\omega \sim \omega_{pi}$, and $k \sim 1/\lambda_D$, was more than 100 times the thermal one. The spectrum of the ion waves has a sharp cut-off for $k \sim 1/\lambda_D$ and the turbulence is highly anisotropic about the direction of the driving electron current.

The overall energy conversion of kinetic energy of the streaming plasma in front to thermal energy behind the shock wave can be determined from the conservation laws independent of a knowledge of the detailed processes which dissipate the energy. However, depending on these processes the ion and electron heating rates may differ considerably.

If the electron density and temperature is measured by Thomson scattering and the magnetic field profiles are known, it is possible to calculate the ion temperature behind the shock by applying the conservation relations. Measurements of the electron temperature in transverse shock waves by laser scattering were reported by Sheffield et al (10) from the University of Texas at Austin, and Martone and Segre (11) from Frascati, Italy, Chodura et al (8) from Garching, Germany and Dippel (12) et al from Jülich, Germany. In good agreement all four measurements show, that below a critical magnetic Mach number of $M_A \sim 2.5 - 3$ only the electrons are heated by scattering from non-thermal collective fluctuations which are the result of ion sound instability. At higher M_A an increasing fraction of the available energy goes to the ions, which are heated by a collisionless energy dissipation mechanism.

Besides measuring the level of turbulence by analysing the spectrum of scattered laser light, other diagnostic techniques have been used to obtain more insight in the nature and magnitude of the collective fluctuations. High frequency electric fields of large amplitude are associated with the occurence of an ion-sound instability in a plasma. One observable spectroscopic effect of the fluctuating electric fields in a plasma is the occurence of satellite lines, disposed symmetrically in pairs about a forbidden atomic line. Because of their large Stark effect, hydrogen-like atoms are not suitable for this method of observing fluctuating fields in a plasma. Chodura et al (8) added 15% helium and used the He I line at 4922 A to measure time-resolved the occurrence of satellite lines in the shock wave. The total intensity of the satellite lines is proportional to $\langle E^2 \rangle$. They are separated from the forbidden line by the frequency of the fluctuating electric field. From the measurements the authors estimate an upper limit for the amplitude of the fluctuating electric fields of $(\langle E^2 \rangle)^{1/2}$ = 6 kV/cm. This value is about two orders of magnitude above the thermal level.

Another spectroscopic method of measuring the small scale electric fields is based on the observation of the linear Stark effect on the profiles of the atomic hydrogen lines H_α, H_β, H_δ. This method was used by Berezin, Dubovoi and Lublin (13) from the Ioffe Physical - Technical Institute in Leningrad to measure fluctuating electric fields of 1 - 4 kV/cm in the turbulent plasma of the Omega device. The plasma was heated by r.f. fields of 100 V/cm. This applied field could not cause the observed line broadening. The authors conclude that the fluctuating electric fields are caused by an ion-sound instability. The appearance of satellite lines favours this interpretation. The observed strong dependence of the fluctuating fields on the magnetic field strength, E increases with B_z, remains unexplained by theory.

The density fluctuation spectrum which occurs during the turbulent heating of a toroidal hydrogen plasma column has been investigated by Sharp and Hamberger (14), Culham Laboratory, England, by using the collective scattering of 2mm microwaves. The heating current pulse of $\sim$ 5 kamps lasts $\sim$ 300 nsec, was produced by electromagnetic induction of a strong electric field ($\sim$400 V cm^{-1}) parallel to the axial confining field (3 kG) of a stellarator (TWIST), and rapidly raises the mean particle energies to $\geq$ keV.

The reported preliminary results show short fluctuations at frequencies above the ion plasma frequency and characteristic of ion-electron streaming instability. Since $\omega \gg \omega_{pe}$, and binary particle collisions can be neglected, the attenuation observed during the pulse cannot be due to absorption and must therefore be attributed to the collective scattering of the microwave energy out of the received beam by the density fluctuations. The r.m.s. level of the density fluctuations for all scattering wave vectors not accepted by the forward receiver was estimated to be $\delta n/n \sim 0.1$.

The electrostatic potential fluctuations in a turbulently heated plasma were also measured in Culham by Jancarik and Hamberger (15). A toroidal magnetically confined plasma of $n = 10^{11} - 10^{13}$ cm^{-3} is heated by applying electric fields of 100-500 V/cm ringing with 1 MHz. The frequency spectra of potential fluctuations were obtained by numerical computation from oscillograms of signals received in the 10 MHz to 2 GHz frequency range from a calibrated differential electric probe with an electrode spacing of 1 mm. The type of spectrum observed depends primarily on the plasma density and the applied electric field. Three distinct types of spectrum have been observed depending on initial conditions.

A. The fluctuation spectrum is concentrated at frequencies $\omega < \omega_{pi}$, when the applied electric field is smaller than the critical field for runaway electrons, E_0. This is interpreted as a spectrum of ion-sound turbulence. The spectral distribution has the shape first predicted by Kadomtsev for steady state ion-sound turbulence in current carrying plasma.

B. For applied electric fields $E \gtrsim 40\ E_0$, the spectrum includes strong components at $\omega \sim 1/2(M/m)^{1/6}\ \omega_{pi} > \omega_{pi}$ which are characteristic for an ion-electron streaming instability. This frequency occurs in short bursts of 20 - 40 nsec duration of very intense signal. Similar burst have been observed by Suprunenko in Kharkov.

C. At very large applied electric fields $E \gtrsim 10^3 E_0$, much higher frequencies in the range of ω_{pe} are observed, which may arise from electron-electron interaction due to runaway electrons.

An interesting feature is the relation between the measured electrical conductivity and the drift velocity V_d in the various regimes. The measured conductivity decreases $\sigma \propto \omega_{pe}/v_d$ in the region of the ion-sound turbulence, A. With increasing drift velocity the conductivity decreases to the Buneman value for the two-stream excited turbulence.

The mechanism of turbulent ion heating in a linear discharge was investigated by Koydan and Ponomarenko (16) from the Institute of Nuclear Physics in Novosibirsk, USSR. The ion distribution function of the heated ions was determined by means of a nine-channel analyser for charge exchanged neutrals. The sensitivity of the analyser is about 5×10^{-11} amp with a time resolution of 10^{-8} sec. The signals of the analyser show that 300- 500 nsec after the start of the current pulse an intense heating of the ions occurs. Above ion energies of 1 keV, the distribution function of the ions agrees satisfactorily with a Maxwellian for $T_i \approx 800$ eV. At lower energies a cold ion group seems to be present in the plasma. While the initial plasma density was 2×10^{13} cm^{-3}, the density of the heated ions is $1 \times 10^{13} cm^{-3}$. This indicates a high efficiency of ion heating in the turbulent discharge. It is assumed that the ion heating occurs due to the onset of an ion-acoustic instability. The soft x-ray spectrum indicates that the electrons are heated earlier in time than the ions at 100 nsec to $T_e = 3 - 5$ keV. However, fast electrons with an energy of about 200 keV have also been observed. This may indicate a possible plasma heating due to two-stream instability.

Demidov and Fanchenko (17) from the Kurchatov Institute in Moscow reported on an investigation of plasma turbulent heating and loss mechanisms in the toroidal machine Vikhr-3. This torus with a 10 cm minor and 150 cm major radius has in addition to the B_z field a quadrupole B_ϕ field which is produced by 4 conductors wound around the torus and carrying antiparallel currents. An electric field of 50 V/cm around the torus was pulsed for

1 μsec. A delayed second current pulse was applied to test the dependence of heating and plasma losses upon initial conditions. With a density of 10^{12} cm^{-3} and heated to $T_e \approx 1$ keV, the exponentially decaying diamagnetic signal could be observed for 30 - 40 μsec.

Charged particles are accelerated in solar flares in the vicinity of zero or neutral lines of magnetic field. The turbulent conductivity of a plasma in a magnetic field with zero lines was experimentally investigated by Syrovatsky, Frank and Khodshaev (18) from the Lebedev Physical Institute in Moscow. A quadrupole magnetic field was produced by four current carrying rods. A plasma with a density of about 10^{13} cm^{-3} was treated with a pulsed electric field of 500 V/cm applied along the zero line of the quadrupole field. The current distribution was measured with magnetic probes and Rogowsky coils. The current carrying region was found to be rather broad in spite of the strong transverse magnetic field which had a gradient of 5×10^3 G/cm. The conductivity in the $T \sim 1$ keV plasma was much smaller than the collisional one.

V. Laser Produced Plasmas

In addition to papers presented in the Dense Plasma session there was an informal meeting on laser produced plasmas arranged during the conference by O. N. Krokhin from the Levedev Physical Institute in Moscow. There is no doubt that the Russians are very much interested in laser produced plasmas. M. S. Rabinovich from the Lebedev Physical Institute in Moscow mentioned in the panel discussion that besides the toroidal confinement scheme one should look for alternative possibilities to achieve fusion and he suggested to consider laser heated plasmas. Krokhin presented some estimates on the power needed to reach the Lawson criterion, $n\tau \gtrsim 10^{14}$. He concluded that power levels of 10^{18} watts would be needed if the plasma expands during the laser pulse duration. Hence fusion cannot be achieved in the gasdynamical phase. Short neodymium laser pulses of 1 nsec or less and 10^5 joules or more would be required to heat an inertially confined dense plasma to thermonuclear temperatures. The low efficiency of about 0.1% of neodymium doped glass lasers represents a distinct disadvantage in the overall energy balance. The possibility to heat a plasma at longer wave length by CO_2 lasers which also have a higher efficiency was mentioned. However it is probably very hard to get CO_2 laser pulses of 1 nsec or less. On the other hand the absorption coefficient for the 10.6 μ wavelength is by two orders of magnitude larger and it should be possible to heat a magnetically confined plasma with a density of $n \approx 10^{17} - 10^{18}$ cm^{-3} with CO_2 laser pulses of longer duration. Some calculations, which seem to contradict Krokhin's opinion were presented by Bobin and Tonon (19), from the Centre d'Etudes de Limeil, France, in a contributed paper on "Fusion by Laser Driven Flame Propagation in Solid DT Targets". The French neodymium laser system consists now of an oscillator and 7 amplifier rods with 4 Pockels cells in between. The laser has a power output of 12 GW and a pulse length of 3.5 nsec. The focal spot size is 80 μ. When focussed on the surface of a solid DD target typically in the order of 7 GW are absorbed. In contrast to the high absorption rates claimed elsewhere, the French investigator observed that 30% of the light is reflected at these high power levels. 2×10^4 neutrons are produced per laser pulse.

Still, the present state laser performances are several orders below the requirements for a laser heated DT fusion reactor. On the other hand if one compares the energy density and the life time of the plasma with the Lawson criterion, then we see that the laser created plasma appears to be in the same situation as other "fusion plasmas". The conditions were derived for a power producing fusion reactor heated by a laser. If a satisfactory efficiency for the overall energy conversion processes in the reactor of about 10% could be achieved, CO_2 laser pulses would be required of 10 μsec in duration and quite reasonable fluxes of 10^{13} - 10^{14} W/cm^2. It is an important advantage of a laser driven pulsed fusion reactor that no expensive B-fields would be needed for confinement. A first important result would be achieved it the energy released by thermonuclear reactions exceeds the laser beam energy. Without electron heat conduction this condition for a positive energy balance is fulfilled when the plasma is heated to 8 keV and the duration of a neodymium laser pulse becomes longer than 300 nsec. In this example the flux is assumed to be 2.3×10^{14} W/cm^2, and the laser energy 7×10^3 joules for a target of $(100\ \mu)^2$ cross section and 3 cm length. This odd shaped target results from the assumption of a steady deflagration structure in the target.

A. Caruso from the Laboratori Gas Gas Ionizzati in Frascati, Italy, reported in an invited paper on the observation of second harmonic generation in laser produced plasmas. Single pulses from a mode-locked neodymium glass laser of 1-5 Joules were used. The two photon absorption fluorescence method indicates subpulses of 2×10^{-12} sec duration separated by time intervals of the order of 10^{-11} sec. The total amount of light reflected from a cylindrical solid deuterium target of 1 mm diameter is less than 10% of the incident light. The laser beam hits the target under an angle to avoid damage of the laser by reflected light. The time integrated spectral analysis of the back-scattered light shows a well defined line at 5,3000 angstrom. Time resolved spectra of the back-scattered light have been obtained which show that the second harmonic generation lasts for about 10^{-10} sec. The intensity of the back-scattered second harmonic line is a fraction of order of 10^{-5} - 10^{-6} of the reflected 10,600 A line. The intensity of the second harmonic is a function of the angle of observation. A maximum occurs at an angle which is smaller than the angle of reflection for the incident beam.

References

1. Paper 18: "The Energy Balance and the Lifetime of Ions in Plasma of Tokamak T-3", by L. A. Artsimovich, A. V. Glukhov, E. P. Gorbunov, M. P. Petrov. I. V. Kurchatov Institute of Atomic Energy, Moscow, USSR, A. F. Ioffe Physico-Technical Institute, Leningrad, USSR.

2. A. A. Galeev, R. Z. Sagdeev, J. E. T. P. 53, 348 (1967).

3. Paper 17: "Current Diffusion and Energy Balance in Tokamak Systems," by Y. N. Dnestrovskii, D. P. Kostomarov, N. L. Pavlova, Moscow State University, Moscow, USSR.

4. Paper 19: "The Plasma Energy in Tokamak T-3 From Electrical and Thomson Scattering Measurements", E. P. Gorbunov† D. P. Ivanov†, N. J. Peacock* D. C. Robinson *, V. Strelkov †.
* U, K. A. E. A., Culham Laboratory, Abington, Berkshire, England.
† I. V. Kurchatov Institute of Atomic Energy, Moscow, USSR.

5. Paper 31: "Directional Ion Fluxes in a Plasma Confined in a Toroidal Magnetic Trap", by M. S. Berezhetsky, S. E. Grebentshikov, I. A. Kossy, I. S. Shpigel. P. N. Lebedev Institute of Physics, Academy of Sciens, Moscow, USSR.

6. D. Pfirsch, A. Schlüter, Rept. Max-Planck Inst., Munich, MPI/PA/7/62, (1962).

7. H. L. Berk, A. A. Galeev, Phys. Fluids, 10, 441, (1967).

8. Paper 56: "On the Mechanism of Energy Dissipation in Collisonless Shock Waves", by R. Chodura, M. Keilhacker, M. Kornherr, H. Niedermyer, K. -H. Steuer, Institut für Plasmaphysik, Garching, Germany.

9. Paper 57: "Measurement of Spectrum and Anisotropy of Turbulence Within a Collisonless Sock by Scattering of Light", by C. C. Daughney, L. S. Holmes, J. W. M. Paul, D. D. R. Summers. U. K. A. E. A., Culham Laboratory, Abingdon, Berks. England.

10. Paper 58: "Electron Temperature Measurements in Oblique and Normal Collisonless Shocks in Magnetized Plasmas", J. Sheffield, G. Decker, A. B. Macmahon, and A. E. Robson, The University of Texas at Austin, Austin, Texas, U. S. A.

11. Paper 59: "Plasma Heating in Low-β Collisonless Shock Waves", by M. Martone and S. W. Segre, Laboratori Gas Ionizzati, Frascati, Rome, Italy.

12. Paper 55: "Collisonless Shock Waves and Anomalous Electron Heating at Very Low Densities", by K. H. Dippel, K. Höthker, E. Hintz Institut für Plasmaphysik, Assoziation KFA-EURATOM, Jülich, Germany.

13. Post-deadline Paper 62 bis: "Stark Effect in a Turbulent Plasma of R. F. Discharge in "Omega" Device", by A. B. Berezin, L. V. Dubovoi B. V. Lublin, Efremov Institute of Electrophysical Engineering, Ioffe Physical-Technical Institute, USSR Academy of Sciences, Leningrad, USSR.

14. Paper 64: "Microwave Scattering from Density Fluctuating during Turbulent Heating", by L. E. Sharp and S. M. Hamberger, U. K. A. E. A., Culham Laboratory, Abingdon, Berkshire, England.

15. Paper 65: "Electrostatic Potential Fluctuations Measured During Current Driven Turbulence", by J. Jancarik and S. M. Hamberger, U. K. A. E. A., Culham Laboratory, Abingdon, England.

16. Paper 63: "Turbulent Heating of Ions by the Current of a Linear Discharge", by V. S. Koydan, A. G. Ponomarenko, Institute of Nuclear Physics, Siberian Division of the USSR Academy of Sciences, Novosibirsk, USSR.

17. Paper 62: "Plasma Turbulent Heating in 'Vikhr - 3' Toroidal Device", by B. A. Demidov, S. D. Fanchencko, I. V. Kurchatov Institute of Atomic Energy, Moscow, USSR.

18. Paper 66: "Turbulent Conductivity of Plasma in Magnetic Field with Zero Line", by S. I. Syrovatsky, A. G. Grank, A. Z. Knodshaev, P. N. Lebedev Physical Institute, Moscow, USSR.

19. Paper 112: "Fusion by Laser Driven Flame Propagation in Solid DT Targets", by J. L. Bobin, G. F. Tonon, Commissariat a l'Energie Atomique, Centre d'Etudes de Limeil, France.

INVESTIGATION OF LASER PRODUCED PLASMAS IN A MAGNETIC FIELD

by

F. Schwirzke

Naval Postgraduate School, Monterey, California 93940, USA

Abstract: The influence of finite conductivity on the dynamics of a laser produced plasma has been studied. The expanding plasma forms an elliptical shell of hot plasma due to enhanced resistive heating of the electrons at the plasma field boundary. The long lasting plasma shell could be utilized as a target plasma in neutral beam injection mirror machines.

High powered lasers are currently applied in the following four areas of the CTR program: 1) Production of a clean plasma within magnetic field configurations for basic studies of collisionless shock wave phenomena, stability and confinement. 2) Utilization of a laser produced plasma as a target in neutral injection mirror machines. 3) Scattering of laser light for plasma diagnostics. 4) Short time plasma heating for thermonuclear neutron production. Neutron emission has been obtained by focussing a giant laser pulse on a solid deuterium target. However, the power levels of the presently existing lasers are far too low to achieve a self sustaining fusion process. For this reason the other above mentioned laser applications seem to be more useful at the present time. The purpose of this paper is to discuss the interaction of a laser produced plasma with a magnetic field and the implications of the results for the creation of a target plasma.

Long confinement times in mirror machines have been achieved recently. In addition, a highly efficient method has been proposed [1] for regaining the energy of the particles which escape through the loss cone by direct conversion. These encouraging results provide the motivation for considering mirror machines as one of the prime types of possible fusion reactors. Estimates show that the ionization probability may be increased tenfold or more in comparison with Lorentz ionization if a laser produced target plasma is utilized [2]. Certainly, it would be highly desirable to keep the laser produced target plasma over a longer time localized within a small core volume of the mirror machine. Obviously the interaction of the expanding laser produced plasma with the magnetic field is of special importance if we want to create a target plasma.

A dense and hot plasma was created in the central region of a magnetic mirror field with a mirror ratio of 2:1 by focussing a 150 MW 20 ns pulse from a Q-switched neodymium laser on the tip of a 30μ pyrex fiber. It is advantageous to use a heavy ion plasma for the investigation of the dynamics of a laser created plasma expanding in a magnetic field because the macroscopic flow velocity is reduced and the behavior of the plasma can be more easily analysed by magnetic probes, Langmuir probes and high speed photography. During the initial expansion phase of the $\beta \gg 1$ plasma the temperature decreases rapidly according to the form $T_r = T_o(r_o/r)^2$ where T_o and r_o are the temperature and radius of the plasma when it becomes transparent. The

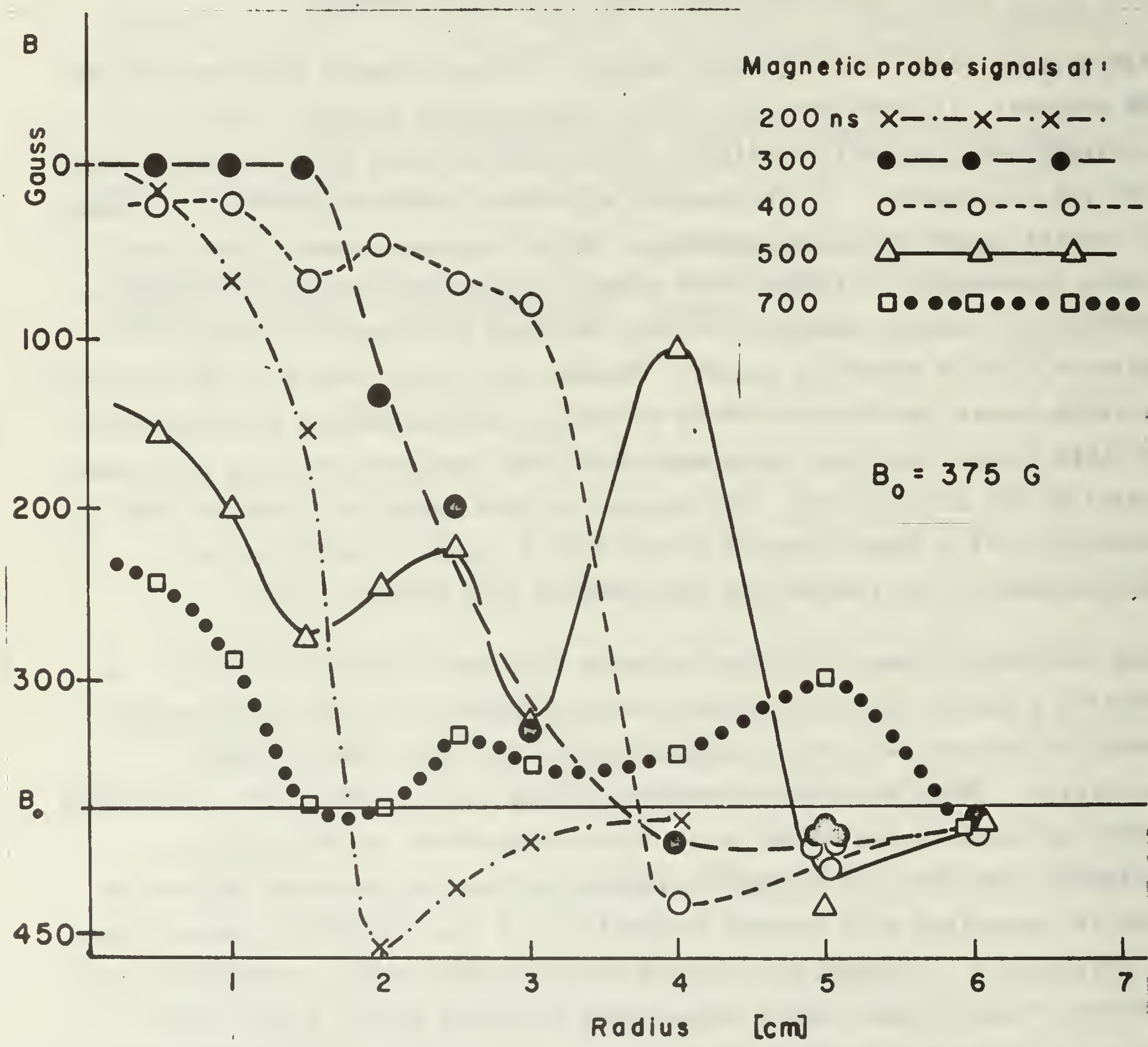

Fig. 1. Magnetic field profiles measured in radial direction across B_o. Parameter is the time elapsed from firing of the laser pulse.

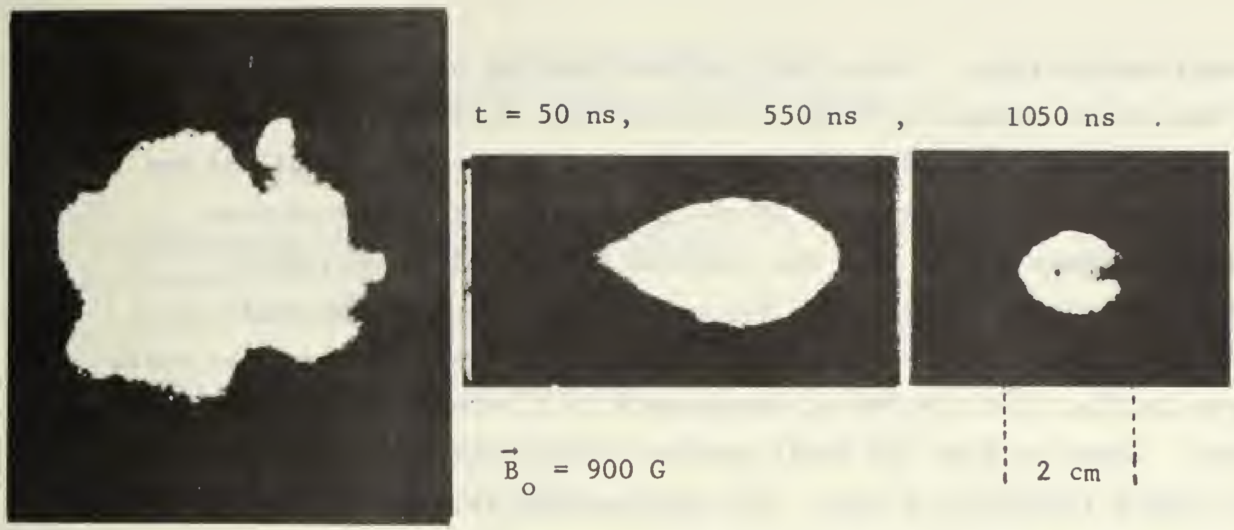

Fig. 2. Image converter photos of laser produced plasma.

rapid decrease of T_r implies that an asymptotic plasma expansion velocity V is reached in a rather short time while $\beta \gg 1$. Resistive effects, associated with surface currents in the front of the plasma expanding against a magnetic field, form the most effective means of rethermalization of the kinetic energy of expansion. The skin depth for which B penetrates into the plasma is determined by the effective resistivity. We would expect from Spitzer's formula for the conductivity σ that with decreasing T_r the width of the front of the expanding plasma, $d = c^2/4\pi\sigma V$, increases proportional to $d \propto T_r^{-3/2}/V$ or as function of the radius $d \propto r^3/V$. The measured magnetic field profiles of Fig. 1 do not show such a relationship between d and r. Furthermore, the magnetic probe measurements, Fig. 1, and the image converter photos of the expanding plasma, Fig. 2, clearly show the development of a shell structure in the plasma at $t \gtrsim 500$ ns.

Resistive heating becomes more efficient with decreasing T_r. Correspondingly, the temperature of the expanding plasma goes through a minimum. Computer calculations show that the minimum value of T_r and the time of its occurence is a function of B_o. With increasing B_o-field the minimum occurs earlier in time and it is less pronounced. The B - field penetrates the whole plasma if at low temperatures d becomes larger than the plasma radius. Later, with increasing conductivity this field will to some extent be "frozen" into the plasma. Even a weak B - field in the plasma reduces the transverse heat flow in the plasma considerably due to the $1/B^2$ dependence of the coefficient of thermal conductivity. Since the resistive heating of the electrons is mainly due to the surface currents, a reduced heat flow backwards into the plasma leads to an enhanced temperature increase in the outer shell of the expanding laser produced plasma. If the growth rate of the two-stream instability becomes larger than the electron - ion Coulomb collision frequency, turbulence developes in the wave front and contributes also effectively to the plasma heating [3]. Actually the half width of the shell structure in Fig. 1 at $t = 500$ ns corresponds to a Bohm-diffusion like heat transport. Later in time the shell remains almost stationary and the density decays relatively slowly. The experimental results indicate that the plasma losses along the field lines are considerably reduced probably due to a captured poloidal field. In conclusion, such a long lasting plasma ring produced by laser irradiation of a pellet would represent a useful target plasma for neutral beam injection machines.

Research sponsored by the Air Force Office of Scientific Research, Office of Aerospace Research, United States Air Force, under AFOSR Grant No. MIPR - 0004 - 69.

References

1. R. F. Post, Bull, Am. Phys. Soc., 14, 1952 (1969).
2. D. O. Hansen, W. Bernstein, B. D. Fried, Bull. Am. Phys. Soc., 14, 1022 (1969).
3. F. Schwirzke, R. Tuckfield, Phys. Rev. Letters, 22, 1284, (1969).

DISTRIBUTION LIST
AFOSR (SREP) PROJECT 9752

	No. of copies
Defense Documentation Center (DDC) Cameron Station Alexandria, Virginia 22314	20
Dean of Research Administration Code 023 Naval Postgraduate School Monterey, California 93940	2
Library Naval Postgraduate School Monterey, California 93940	2
Air Force Office of Scientific Research (SREP) 1400 Wilson Boulevard Arlington, Virginia 22209	25
Dr. Winston H. Bostick Department of Physics Stevens Institute of Technology Hoboken, New Jersey 07030	1
Dr. C. L. Dailey Space Technology Laboratories TRW Systems Inc. One Space Park Redondo Beach, California 90278	1
Mr. A. C. Ducati Plasmadyne Division GEOTEL Inc. Santa Ana, California 92702	1
Dr. Robert A. Gross Applied Science & Engineering Dept. Columbia University New York, New York 10027	1
Dr. C. D. Hendricks Dept. of Electrical Engineering University of Illinois Urbana, Illinois 61801	1

	No. of copies
Dr. M. Kristiansen Dept. of Electrical Engineering Texas Technological College Lubbock, Texas 79409	2
Dr. G. S. Janes Avco Everett Research Laboratory AVCO Corporation Everett, Massachusetts 02149	1
Dr. M. L. Pool Physics Department Ohio State University Research Foundation Columbus, Ohio 43212	1
Prof. Robert Eustis Mechanical Engineering Dept. Stanford University Stanford, California 94301	1
Dr. Richard M. Patrick Avco Everett Research Laboratory AVCO Corporation Everett, Massachusetts 02149	1
Dr. Norman C. Jen City College Research Foundation City University of New York New York, New York 10031	1
Dr. Alan F. Haught United Aircraft Research Laboratory United Aircraft Corporation East Hartford, Connecticut 06108	1
Dr. Donald A. Dunn Dept. of Electrical Engineering Stanford University Stanford, California 94305	1
Dr. Willard H. Bennett Physics Department North Carolina State University Raleigh, North Carolina 27607	1

	No. of copies
Dr. John B. Dicks Department of Physics University of Tennessee Space Institute Tullahoma, Tennessee 37388	1
Prof. Daniel R. Wells Physics Department University of Miami Coral Gables, Florida 33124	1
Dr. Robert L. Hickok Central Research Division Mobil Oil Corporation Princeton, New Jersey 08540	1
Mr. S. T. Demetriades President, STD Research Corp. Pasadena, California 91106	1
Dr. R. M. Measures Institute for Aerospace Studies University of Toronto Toronto, Canada	1
Dr. Moshe J. Lubin Dept. of Mechanical & Aerospace Science University of Rochester Rochester, New York 14627	1
Professor F. Cap Institute for Theoretical Physics University of Innsbruck Innsbruck, Austria	1
Dr. Nima Geffen Dept. of Applied Mathematics Tel-Aviv University Ramat-Aviv Tel-Aviv, Israel	1
Dr. Joseph Verdeyen Dept. of Electrical Engineering University of Illinois Urbana, Illinois 61820	1

	No. of copies
Mr. John Wyatt Berkeley Analytical Sciences Service Inc. Box 1250 Berkeley, California 94701	1
Dr. James McCune Dept. of Aeronautics & Astronautics Massachusetts Institute of Technology Cambridge, Massachusetts 02139	1
Dr. Jan Rosciszewski Air-Vehicle Corporation 8873 Balboa Avenue San Diego, California 92123	1
Dr. Charles S. Cook General Electric Company Valley Forge, Pennsylvania 19101	1
Dr. Fred Schwirzke Naval Postgraduate School Physics Department Monterey, California 93940	5
Dr. A. J. Lichtenberg Dept. of Electrical Engineering and Computer Sciences University of California Berkeley, California 94720	1
Dr. Sheldon Gruber Case Western Reserve University Cleveland, Ohio 44106	1
Dr. A. Anastassiades Nuclear Research Center Greek Atomic Energy Commission Aghia Paraskevi, Attikis Athens, Greece	1
Dr. John G. Siambis Dept. of Electrical Engineering Carnegie Mellon University Pittsburgh, Pennsylvania 15213	1

	No. of copies
Commander Gayland J. Mischke Department of the Navy Office of Naval Research Power Branch (Code 429) Washington, D. C. 20360	2
Commanding Officer Office of Naval Research Branch Office Box 39, Fleet Post Office New York, New York 09510	1
Director, Technical Information Division Naval Research Laboratory Attn: 2027 Washington, D. C. 20390	1
Mr. Frank J. Mollura Rome Air Development Center Attn: EMEAM Griffiss AFB, New York 13440	1
Mr. Frank Shields U. S. Army Mobility Equipment Research & Development Center Fort Belvoir, Virginia 22060 Attn: SMEFB-EA	1
Dr. B. Lubarsky Chief, Space Power Systems Division NASA, Lewis Research Center 21000 Brookpark Road Cleveland, Ohio 44135	1
Mr. J. Mullin Headquarters NASA (OART) Washington, D. C. 20546	1
European Office of Aerospace Research Attn: Lt. Col. Richard Boverie (ERTE) APO New York 09667	1
Mr. Clifford Hurd AF Rocket Propulsion Laboratory (RPRE) Edwards AFB, California 93523	1

	No. of copies
AF Aero Propulsion Laboratory Wright-Patterson AFB, Ohio 45433	
Mr. Robert Cooper (APIE-4)	1
Mr. Philip Stover (APIE)	1
Mr. Robert Johnson (APIE-2)	1
Dr. Sinclair Physics Section Atomic & Molecular Physics National Science Foundation 1800 G Street, N. W. Washington, D. C. 20550	1
Dr. Morton Levine Branch Chief (AFCRL/CREA) L. G. Hanscom Field Bedford, Massachusetts 10731	1
Colonel William K. Moran, Jr. Aerospace Research Laboratories Wright-Patterson AFB, Ohio 45433	3
Major B. W. George Hq AFSC (SCTSP) Andrews AFB, D. C. 20331	1
Dr. Hans Von Ohain Chief Scientist ARL (ARD-1) Wright-Patterson AFB, Ohio 45433	1
Dr. R. Gould Research Division U. S. Atomic Energy Commission Washington, D. C. 20545	1
Wolfgang E. Moeckel NASA, Lewis Research Center Propulsion Division 21000 Brookpark Road Cleveland, Ohio 44135	1
Dr. Robert Hirsch Research Division U. S. Atomic Energy Commission Washington, D. C. 20545	2

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)

Naval Postgraduate School
Monterey, California 93940

2a. REPORT SECURITY CLASSIFICATION
UNCLASSIFIED

2b. GROUP

3. REPORT TITLE

Part A - Report on the IV European Conference on Controlled Fusion and Plasma Physics - Rome, Italy, 31 August - 4 September 1970

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Scientific Interim

5. AUTHOR(S) (First name, middle initial, last name)

F. Schwirzke

6. REPORT DATE
26 January 1971

7a. TOTAL NO. OF PAGES
32

7b. NO. OF REFS
22

8a. CONTRACT OR GRANT NO. MIPR 70-0001

b. PROJECT NO. 9572-01

c. 61102F

d. 681308

9a. ORIGINATOR'S REPORT NUMBER(S)
NPS-61SW71011A

9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT

11. SUPPLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY
AF Office of Scientific Research (SREP)
1400 Wilson Boulevard
Arlington, Virginia 22209

13. ABSTRACT

The titles of the 17 sessions and the 6 invited lectures are summarized in the introduction. Concerning the content of the 191 presented papers, only the ones referring to toroidal confinement, laser produced plasmas, collisionless shocks and turbulent heating are reviewed in this report, as for example: papers presented by the Russian participants on particle confinement, energy balance, ion and electron thermal conduction, anomalous resistivity, current diffusion and skin depth in tokamaks.

The second part of the report contains the paper No. 114, "Investigation of Laser Produced Plasmas in a Magnetic Field", by F. Schwirzke. All mentioned papers have been published in the conference book entitled, Fourth European Conference on Controlled Fusion and Plasma Physics, Rome, Italy, C. N. E. N. Ufficio Edizioni Scientifiche, (1970).

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Conference Report						
Toroidal Confinement						
Collisionless Shocks						
Laser Produced Plasma						